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Blockchain for healthcare data management: opportunities, challenges, and future recommendations

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Abstract

Today's healthcare data management systems are facing key challenges in terms of data transparency, traceability, immutability, audit, data provenance, flexible access, trust, privacy, and security. Also, a large portion of existing healthcare systems leveraged for managing data are centralized that pose potential risks of single point of failures in case of natural disasters. Blockchain is an emerging and disruptive decentralized technology that has the potential to significantly revolutionize, reshape, and transform the way data are being handled in healthcare industries. In this paper, we discuss how leveraging blockchain for healthcare data management systems can lead to stimulate innovations and bring major improvements. We present the key blockchain features and characteristics. We discuss the premier advantages of adopting blockchain technology along with opportunities for healthcare industries. We present recent on-going projects and case studies to show the practicality of blockchain technology for various healthcare applications. We identify and discuss important open research challenges hindering the successful adoption of blockchain in the healthcare sector. Finally, we outline several future research directions.

Keywords Blockchain · Healthcare · e-Health · emHealth · Healthcare data management

1 Introduction

The rapid advances in the internet of things (IoT) paradigm have revolutionized healthcare industries by bringing major improvements in terms of e-health/medical records (EHR/EMR), prescription drug data, and insurance information [1, 2]. The IoT-based medical devices can help to collect invaluable patient data, automate workflows, provide insights on disease symptoms and trends, facilitate in terms of remote caring, and provide patients more control over their lives and treatments [3–5]. With the IoT devices, patients can be monitored in real-time. Also, they can reduce the need for visiting hospitals for routine health checkups. Connected home health monitoring systems can help to reduce hospital stays or readmission costs. The IoT-enabled medical devices can assist in diagnosis through alerts and trigger notifications before it becomes serious [6–9]. Sensors installed onto various parts of a patient's medical apparatus can gather and send data to the hospital, where a health practitioner can analyze it for the possible abnormalities.

Undoubtedly, developments of the IoT have led to continuous innovations in the healthcare sector [10, 11]. However, handling of EHR/EMR in a secure manner has become very challenging because the data are spread across various medical facilities [12]. Most of existing healthcare systems are centralized that are vulnerable to single point of failures and information leakage due to the rise of cybersecurity attacks [13]. The leakage of patients' personal and critical information can lead to serious consequences. Also, the current medical systems fall short to provide transparency, trustful traceability, immutability, audit, privacy, and security, while managing EHR/EMR [14]. Considering these challenges in the current healthcare systems, blockchain technology has the potential to resolve

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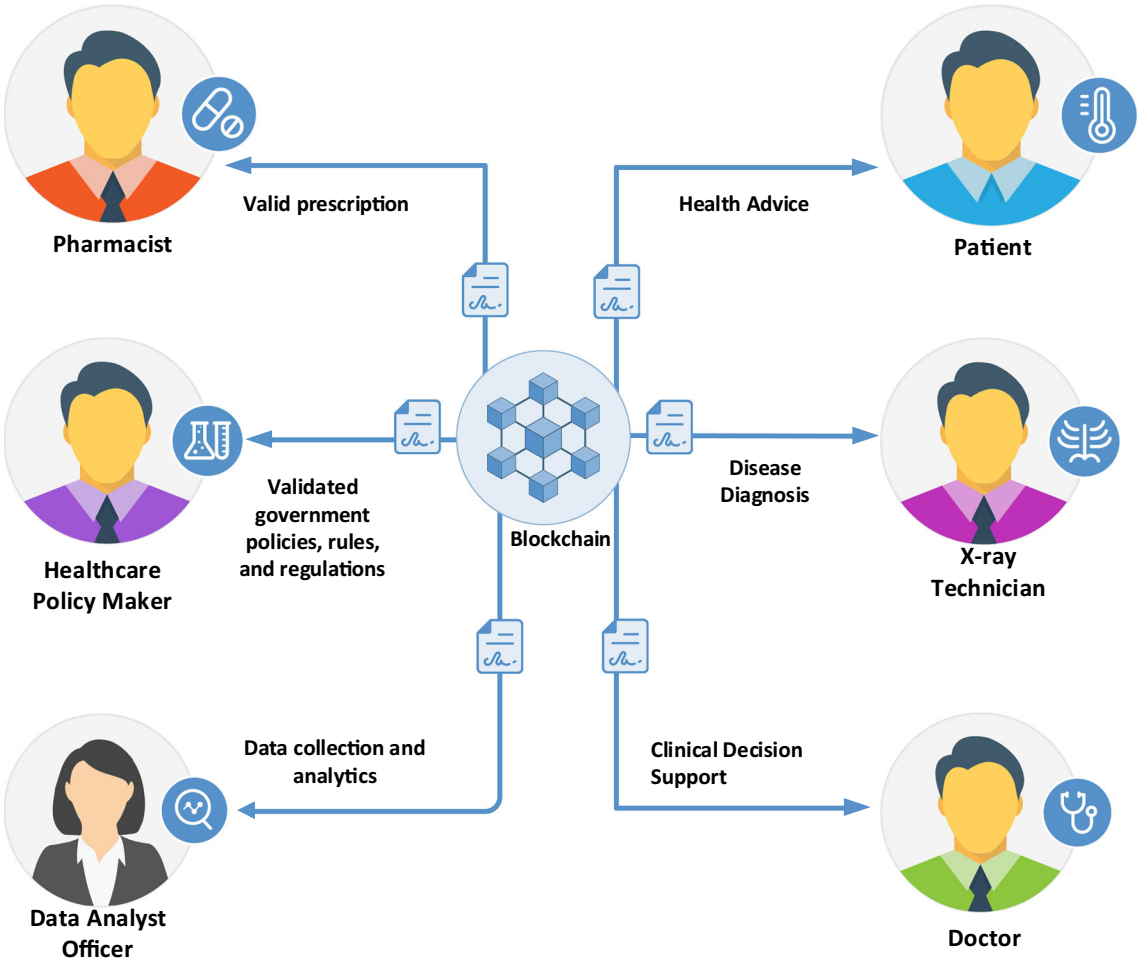

Fig. 1 Blockchain-enabled healthcare systems

them [15–18]. It is estimated that blockchain adoption can lead to saving of up to $100–$150 billion per year by 2025 in data breach-related costs and through a reduction in frauds and counterfeit products [19].

Blockchain is a promising technology that can assist to streamline healthcare data management operations by providing unprecedented data efficiency and enforcing trust [20–25]. It offers a wide range of prominent and built-in features, such as decentralized storage, transparency, immutability, authentication, data access flexibility, interconnection, and security, thereby enabling widespread use of blockchain technology for healthcare data management [26, 27]. Figure 1 illustrates the blockchain-enabled healthcare systems [18].

Blockchain uses the concept of smart contracts that present terms and conditions on which all the healthcare partners involved in the network are agreed upon, and thus no intermediary is required [28, 29]. It reduces unnecessary administrative costs. Blockchain mainly relies on three concepts, such as peer-to-peer networks, public key cryptography, and consensus mechanisms [30]. Based on managing permission, blockchain is divided into three categories; namely, public, private, and consortium blockchains [31]. In public blockchains, any individual connected to the Internet can participate in the consensus procedure. Public blockchains integrate incentives and encrypted digit verification using proof-of-work or proof-of-stake mechanisms. The entire public blockchain system is transparent, wherein the identity of each participating individual remains pseudo-anonymous. In a private blockchain, only a single organization has control over the network. Therefore, such a type of blockchain requires a trustworthy agent to reach the consensus. The consortium blockchain combines the advantages of both public and private blockchain networks. It is only suitable for certain organizations that aim to streamline communication amongst one another. Based on specific requirements or use case scenarios, healthcare organizations can employ any type of blockchain network as all of them have their pros and cons.

In the past, several surveys have been conducted on the adoption of blockchain technology into different healthcare

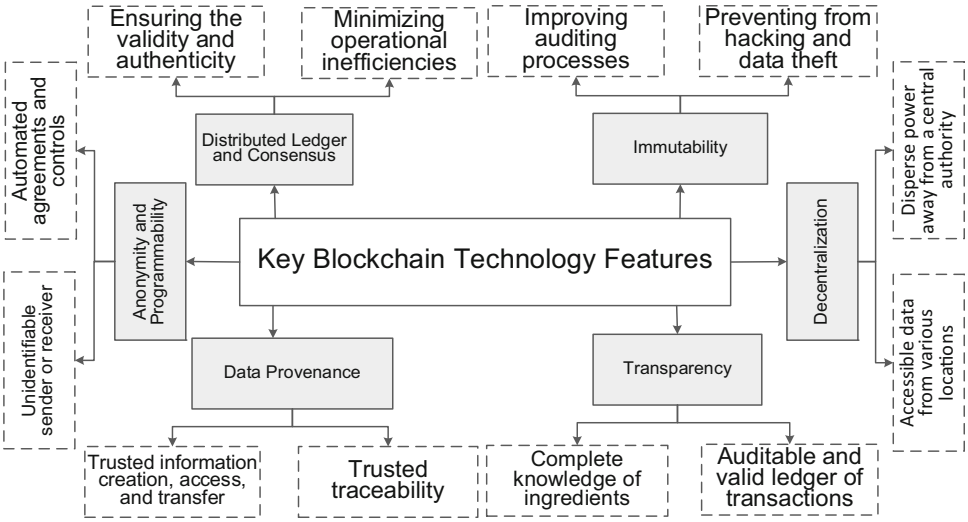

Fig. 2 Prominent blockchain features for healthcare applications

applications [16, 32–38]. Our survey is distinctively different from them in terms of broader focus and content-wise. Besides, several other important aspects of blockchain technology with respect to intrinsic features, emerging opportunities, and potential challenges, which are presented in the current survey, have not been reported in previous ones. In this paper, we explore the role of blockchain technology in terms of healthcare data management. Our key contributions are listed below:

- We provide insightful discussions on the key blockchain features along with their notable benefits in healthcare industries.
- We explore and discuss the main opportunities offered by blockchain technology in the healthcare sector.
- We discuss several case studies to show the practicality of the blockchain-based healthcare systems.
- We identify and discuss important open research challenges, and outline several future recommendations.

These contributions are presented in various Sects. 2–6. Our concluding remarks and future recommendations are outlined in Sect. 7.

2 Key blockchain technology features

Figure 2 outlines six blockchain features that can bring remarkable advances in existing healthcare systems. Further discussion is provided in the next subsections.

2.1 Decentralization

Most of the current healthcare facilities or institutions are based on centralized systems, resulting in overpowering a single entity. There are several crucial limitations of the centralized approach, e.g., single point of failure stemming from natural disasters or bad intents, any unintentional or deliberate malfunctioning at the top of the hierarchy can bring a negative impact on the entire healthcare systems. Blockchain allows decentralization that leads to distribute and disperse power away from a single or central authority, thereby making blockchain more resilient, efficient, and democratic technology [39]. Through decentralized principles, blockchain can help to improve health data access and security of patient information, and thus can overturn the healthcare hierarchy by enabling the development of new systems in which patients can manage their data.

2.2 Transparency

Transparency is one of the most appealing features of blockchain technology. Enabling transparency of the health data can help to provide a fully auditable and valid ledger of transactions [40]. The current healthcare data management systems are unable to provide privacy, security, and transparency at the same time together. Blockchain not only enforces a higher level of transparency but also ensures privacy and provides authorized control over the healthcare data in a parallel way. All the health-related transactions performed on the public blockchain are searchable and traceable. The level of transparency offered by blockchain technology can empower healthcare institutions to have complete knowledge of ingredients used to make a medicine, circumstances under which it was manufactured, the workflow between wholesalers, distributors, resellers, and customers [41]. Greater transparency can undoubtedly make healthcare services more efficient. Blockchain achieves transparency through encryptions and control mechanisms.

2.3 Immutability

One of the major concerns raised by the current centralized healthcare systems relates to healthcare data immutability as they are prone to hacking and data theft. Immutability is another striking feature of blockchain technology. It refers to the ability of a blockchain ledger to remain unaltered and untamperable. This striking feature has the potential to reshape and transform the auditing process into a fast, efficient, and cost-effective procedure. Also, it can enforce more trust and provide integrity of the health data, which is used and shared by medical institutions. Blockchain achieves immutability through cryptographic hashing. All transactions are registered on digital blocks, wherein each blockchain contains a hash, which is created based on the previous block's hash and the new information entered into the new block [42].

2.4 Data provenance

Data provenance is essential for healthcare to establish a certain level of trust in health data by providing complete information about its creation, access, and transfer [43]. Blockchain ensures health data provenance by enabling track changes to data from its origin to the current form. Storing historical health records on blockchain can enhance trustworthiness for data validation and audit purposes. Blockchain can provide secure health data provenance by preventing healthcare systems from unauthorized access and alteration. Also, it enables trusted traceability in healthcare industries. Blockchain uses a time-stamping process that involves computing hash values of the provenance record, which are transferred to consensus nodes that ensure keeping a consistent ledger of all valid transactions.

2.5 Distributed ledger and consensus

Combining technological key features, such as distributed ledger and consensus algorithms can enable blockchain to offer a series of benefits. Distributed ledger technology (DLT) can minimize operational inefficiencies, resulting to save administrative costs. Through DLT, all stored health data are shared multiple times among all blockchain nodes, wherein each information is easily verifiable and accessible for anyone within the network. Blockchains self-update

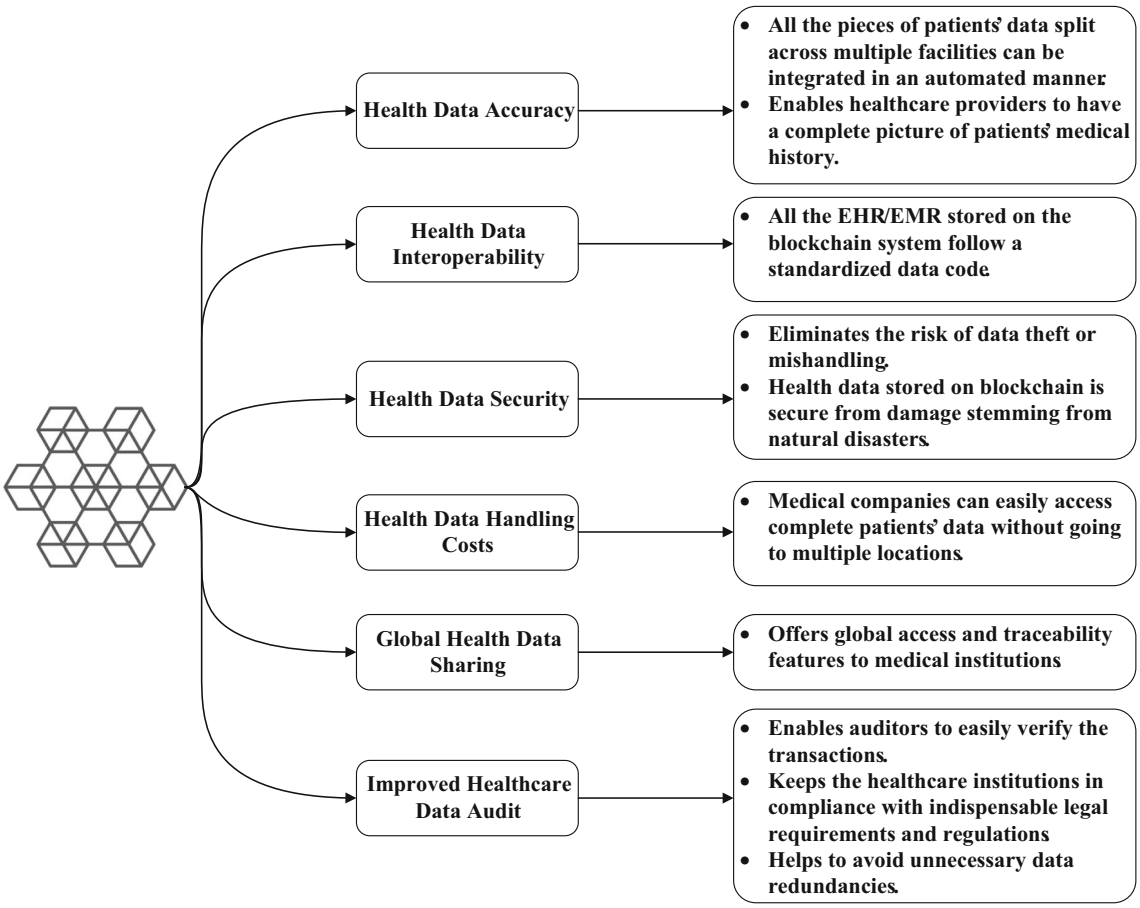

Fig. 3 Benefits of leveraging blockchain technology for healthcare data management systems

within a certain interval of time, thereby ensuring that data are consistent and synchronized with other files. On the other hand, consensus algorithms are responsible for approving transactions on a chain. They enable all stakeholders involved in healthcare systems to agree on a single source of truth. Also, they help to ensure the validity and authenticity of blockchain transactions.

2.6 Anonymity and programmability

Anonymity and programmability are some important features of public blockchains. Anonymity ensures that identities of senders or receivers participating in transactions remain unidentifiable. The programmability feature enables automation of new transactions and controls through smart contracts. The smart contracts contain self-executable codes that are based on the agreements between buyers and sellers. These codes help to control the execution of transactions that are traceable and irreversible. They permit trusted transactions and agreements to be carried out between anonymous parties without involving any third party or any external enforcement procedure.

3 Benefits of blockchain technology in healthcare data management

Figure 3 outlines the main benefits of leveraging blockchain technology for healthcare data management systems. These benefits are discussed in detail in the following subsections.

3.1 Health data accuracy

A patient's medical data are usually fragmented across many facilities, medical care centers, and insurance providers [44]. To get an accurate patient's entire medical history, all the pieces of a patient's data need to be integrated in an automated manner. This can be achieved by storing all patients' medical data (e.g., prescriptions history, symptom data, treatment method, facilities acquired, payment information, and other information) on blockchain which always maintains up-to-date, traceable, and tamper-proof records [45]. This enables healthcare professionals to provide efficient, timely, and proper treatments to patients. Using blockchain technology, healthcare providers can have a complete picture of patients' medical history. All the stored data on blockchain are immutable, transparent, traceable, and secure [38].

3.2 Health data interoperability

Interoperability refers to an ability to exchange information between systems made by different manufacturers. Most of EHR/EMR products are based on different clinical technologies, technical specifications, and functional capabilities [46, 47]. Such differences hinder to create and share data in one format. In certain cases, EHR systems built on the same platform are not even interoperable because they are designed to meet some specific needs and preferences of a health institution. To make two EHR systems interoperable, the transmission messages should be based on standardized coded data [48]. However, the lack of standardized data is a crucial issue that limits the ability to share data electronically for patient care. This limitation can be overcome by using a blockchain-based healthcare data management system. All the EHR/EMR stored on the blockchain system follow a standardized data code, and thus it can easily be accessed and utilized by any healthcare-related facility.

3.3 Health data security

Since the past decade, many healthcare organizations have fallen victim to preventable cybersecurity attacks [49]. A large number of healthcare industries are utilizing manual systems based on centralized infrastructure for handling digital medical records. Such systems have become quite outdated, and thus they can easily be modified with fraudulent intent [44]. Also, medical records can be lost in case of natural disasters because centralization is vulnerable to the single point of failure. Blockchain can help to eliminate the risk of data theft or mishandling through the immutability feature based on cryptographic principles. Health data stored on blockchain are also secure from damage stemming from natural disasters or medical facility collapse because the same data are stored on multiple locations, so there is no central point of failure.

3.4 Health data handling costs

High handling cost associated with patient data retrieval and transfer is another major concern raised by the current healthcare systems. In most of cases, a patient medical record is split across various health facilities. Collecting complete medical records of the patient from manual or disorganized hospital record management systems can lead to excess time and costs [50]. Blockchain technology can help to reduce the administrative cost posed by third parties involved in the current healthcare systems [51]. Also, it enables flexible data access to the patient medical record, which is gathered and stored from various sources, such as

patient documentation, personal wearable and handheld devices, EMRs, to name a few. In this way, blockchain can assist in reducing the costs of medical companies because they can easily access complete patients' data without going to multiple locations where such data used to be stored.

3.5 Global health data sharing

In certain medical emergency scenarios, a thorough knowledge of a patient's past medical history is mandatory before prescribing any medication for proper treatment [52]. For example, a patient suffering from a serious kind of disease traveled outside of country, and may require to consult with a doctor in case of some sudden emergency. In such a case, a medical professional usually requires a patient's prior medical record to offer better and quality healthcare services. The patient's medical history can help doctors to analyze various aspects, such as a past medicine history, drug allergy information, and records of prior treatments, which can lead to devise more optimal treatment strategies. However, most of current healthcare management systems based on manual storage and processing methods, and thus they do not offer global access and traceability features [53]. These features can be achieved through blockchain technology.

3.6 Improved healthcare data audit

Audits are carried out in healthcare industries to verify whether or not they follow certain policies, procedures, rules, regulations, and laws imposed by healthcare institutions. An auditing process helps to evaluate the effectiveness of a healthcare compliance plan through systematic and objective assessments. Today's most of healthcare data management systems are manual and lack intelligent coordination and integration functions. Also, they are vulnerable to data breach and unauthorized modifications. Consequently, such limitations hinder the auditing process and its quality. Blockchain technology facilitates healthcare institutions to manage their data in a verifiable, tamper-proof, and permanent way, thereby proving the trustworthiness of stored health data. This enables auditors to easily verify the transactions performed on blockchain platforms. Blockchain-based healthcare data auditing can assist to improve the quality of patient services, as well as to keep the healthcare institutions in compliance with indispensable legal requirements and regulations. Also, it can help to avoid unnecessary data redundancies.

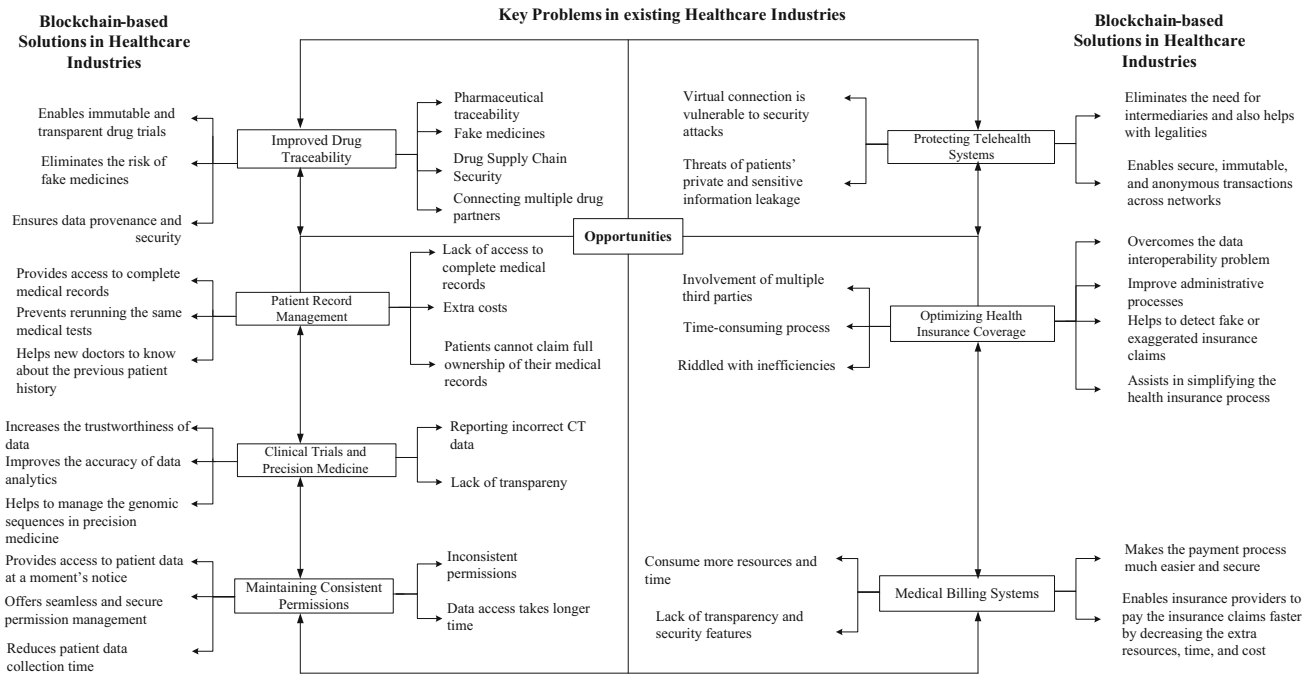

Fig. 4 Blockchain opportunities in healthcare industries

4 Opportunities

In this section, we briefly discuss how blockchain technology can assist in streamlining healthcare data management operations by bringing major improvements, as summarized and shown in Fig. 4.

4.1 Improved drug traceability

In the healthcare industry, drug fraud has become a widespread problem. Once the drug manufacturing process is completed, it needs to be transferred to the wholesale distributors from the production stocks, who further transfer it to the retail companies which sell it to the customers. During this supply chain cycle, there is always a risk of fake medicines being entered [54, 55]. It has been reported that the counterfeit drug market is worth $200 billion annually [56]. The health research funding organization reported that around 10%-30% of drugs sold in the world are fake. These statistics indicate that the pharmaceutical industries are highly vulnerable to fake medicines. Blockchain technology can help to keep track of the manufacturing chain of the drug [57, 58]. Blockchain-based transactions are immutable and have timestamped, which ensure that the information cannot be tampered with. Pharmaceutical industries can either employ public or private blockchain systems according to their business needs. Using the blockchain technology, one can get the complete trail of the drug. Once the drug moves from one place to another, its movement information can be stored on the blockchain which helps to improve the drug traceability and reduces the risk of counterfeit medicines.

4.2 Patient record management

Generally, each patient is unique so similar patient strategies cannot be applied due to inter-individual variability [59]. Therefore, it is essential to have access to complete medical records to provide personalized care. However, sharing such records among the medical community has become a very crucial issue because today's most of the medical systems do not ensure trust, privacy, and security [60]. Also, patients cannot claim full ownership of their medical records because they can also modify or delete the information from their medical records. In most cases, when patients shift to another facility they need to repeat the tests previously done, which pose additional costs. Blockchain is a potential technology that can help to overcome the aforementioned challenges. It stores data over a decentralized peer-to-peer network, which is only accessible using smart contracts, as shown in Fig. 5. Such data can be transferred from one hospital to another without worrying about misuse. Consequently, it helps new doctors to know about the previous patient history, which leads them to better understand the situation and treat them accordingly. Also, blockchain helps to reduce the additional costs because patients do not need to repeat diagnostic tests that were completed earlier. Each copy of the patient record is stored on multiple nodes involved in the blockchain network, thereby making it transparent and corruption-free [61].

4.3 Clinical trials and precision medicine

Blockchain technology can increase the trustworthiness of data collected during the clinical trial (CT) research. It ensures data integrity, which leads to address the problem of reporting incorrect CT data [62]. It provides more transparency and helps to improve the accuracy of data analytics, which can be performed on the data collected from the CTs. Leveraging blockchain for CTs research can help to address several major challenges, such as patient recruitment, tracing and auditing the clinical supply chain, restoring integrity to trial data, and reducing the overall time to conduct trials. In precision medicine, blockchain can be used to manage the genomic sequences, which helps to proactively treat all sorts of diseases and illnesses caused by a genetic disorder [63]. It has been reported that 10% of the chronic diseases that occur in adult populations are genetically inherited. Such diseases and illnesses can be treated proactively by understanding individuals' DNA profiles, which require genomic sequencing. However, there exist challenges, such as interoperability of DNA data and the willingness of organizations to share such data with another that hinder this from happening. Blockchain-based DNA data storage can enable individuals to own and control their data. This eliminates the need for the centralized databases owned by third parties, which are highly vulnerable to hacking. As individuals' data are securely stored on blockchain networks, they can share their data with anyone for medical research, public health studies, and drug development.

4.4 Maintaining consistent permissions

In medical emergencies, healthcare professionals require to have easy access to patient data at a moment's notice. Inconsistent permissions can lead to block a patient's data access in an emergency, which poses a direct danger to the patient life [64]. Blockchain technology can offer two solutions in terms of seamless and secure permission management. Blockchain-based smart contracts can help to grant access using predetermined rules agreed upon by all individuals involved in the contract. These contracts can be customized to automate different workflows. On the other

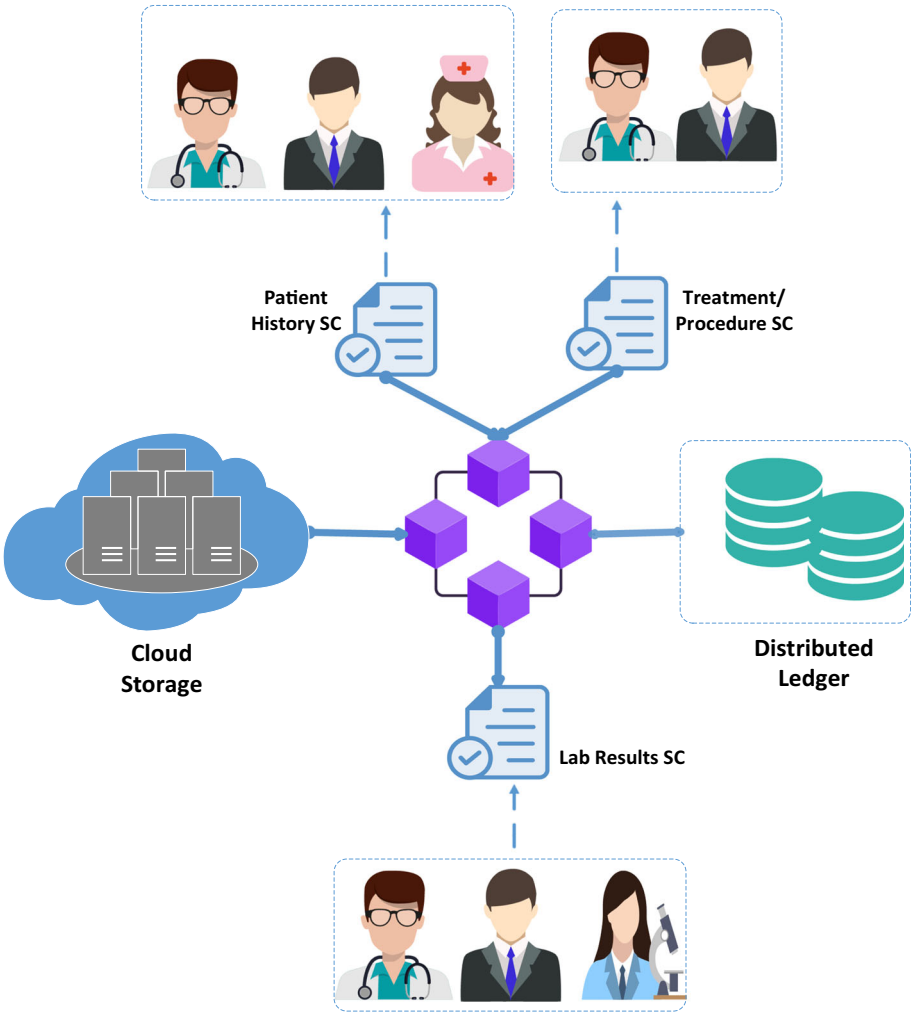

Fig. 5 A simplified example of blockchain-based patient record management

hand, cryptographic keys enable patients to manage access control. Each patient has a master key which helps to unlock healthcare data. The patient can also share its copy to medical practitioners or hospitals when needed. Read and write access privileges can also be added through smart contracts. Blockchain-based smart contacts and cryptographic keys can help to minimize the errors that used to happen due to human negligence. Also, blockchain reduces patient data collection time.

4.5 Protecting telehealth systems

Although telehealth systems have potential to overcome geographic barriers in healthcare, they are vulnerable to cybersecurity attacks. If the virtual connection established between a doctor and patient gets compromised, it can compromise patients' sensitive information, such as household activities, routine data transmissions, in-house brand information, to name a few [65]. The success of telehealth systems mainly depends upon addressing security and privacy concerns. Blockchain can help to adequately provide trust, security, and privacy protection in telehealth systems. It can help to establish a seamless exchange of data without any intermediary that increases consumer confidence in the telehealth systems. It enables doctors to store detailed patient history, treatment/procedure records, and laboratory results in a decentralized, accessible, traceable, and immutable manner. One of the main hurdles in the adoption of blockchain technology into telehealthcare systems is that it can increase the cost for patients who already reside in remote areas whereby resources are very limited.

4.6 Optimizing health insurance coverage

Presently, most insurance companies are based on centralized systems and technologies to store and process their data. Typically, multiple third parties or middlemen are involved throughout the life cycle of a health insurance policy. Moreover, in the insurance world, information is shared among various stakeholders, which makes it a tedious and time-consuming process [66]. Evidently, the

current medical insurance systems are riddled with inefficiencies. Blockchain technology offers an unprecedented level of transparency because it logs all transactions performed on it in a way, which is decentralized, tamper-proof, traceable, immutable, and secure. Blockchain has the potential to overcome the interoperability problem. Using smart contracts, agreement records, transactions, and other information can be collected in an automated manner, which can lead to improving administrative processes. Also, smart contracts can help to detect fake or exaggerated insurance claims. Greater transparency is another benefit of blockchain technology because it enables physicians to see patients' health coverage. Blockchain can assist in simplifying the health insurance process and improving provider directory accuracy through consensus protocols. Hence, blockchain is incredibly a valuable proposal for the health insurance industries.

4.7 Medical billing systems

In the past, traditional modes of patient billing systems have been exposed to various types of frauds [67]. Also, the current billing process consumes more resources and time to generate billing information. Complex coding involved in the medical billing system is one of the main reasons that causes unintentional billing inaccuracies, e.g., duplicating processes or incorrect filings. Combining computer-assisted coding methods with blockchain systems can lead to optimize the medical billing systems. Blockchain is a promising technology that can make the payment process much easier and secure compared to traditional billing approaches that in most of cases take unusual delay to claim the bills. Specifically, in case of insurance claims, where traditional payment systems used to cause even more delay to pay the bills. Blockchain can alleviate such limitations by storing all the data in an immutable manner, which enables insurance providers to pay the insurance claims faster, decrease the extra resources, time, and cost.

5 Recent case studies

This section discusses the recent case studies and ongoing projects toward the deployment of blockchain technology worldwide. The purpose is to show how blockchain technology has been leveraged to bring innovations and advancements in terms of healthcare data management.

5.1 Estonian e-health system

The rapid innovation in computing technology and implementation of e-solutions have revolutionized Estonia's healthcare system [68–70]. In Estonia, 95%-99% of patients have electronic health (e-health) records (e.g., prescriptions, queries by patients, and billing data) that can be tracked and accessed in an authorized manner via e-patient portals. The e-portal enables a doctor to access patients' records (e.g., test results and X-rays) from a single file. In 2016, the Estonian government has initiated a blockchain-based project to secure the health records and system access logs of its 1.3 million residents. The project aims to store the log files that help to keep a track record of all the data processing activities performed on the health records. The prominent benefits of blockchain technology can lead to mitigate the risk of data breaches caused by a malicious hacker or a fraudulent insider in the healthcare sector. A private digital ledger was used to record and timestamp of each instant of access to patient medical data. The cryptographic hash functions create an unchangeable audit trail of the patient data. The project has potential to achieve the goal of having real-time awareness of the integrity of the stored patient data, which enables administrators to identify breaches and act timely to limit the damage. Furthermore, it envisions to improve the cost-effectiveness, robustness, and efficiency of the Estonian healthcare system in a manner, which is decentralized, secure, transparent, tamper-proof, immutable, and auditable.

5.2 Blockchain for healthcare and pharma data in UAE

The Ministry of Health and Prevention (MoHAP) of the UAE has announced the launch of a blockchain-based platform for storing healthcare data (e.g., healthcare facilities, medical practitioners, and medications) [71, 72]. The primary objectives of the platform are to improve storage and strengthen data security across the national healthcare systems. The blockchain-based system is expected to streamline the search for health practitioners, their medical license information, pharmaceutical data, and government and private facilities through MoHAP's application. This blockchain-based application is also expected to provide the most reliable and unchangeable drug details in terms of manufacturing, approved agent, active substance, and price. The MoHAP's solution can be leveraged for keeping the track record of healthcare workers and organizations, resulting to provide easier verification to government entities. Moreover, it helps to improve data validation and consistency, which further leads to enforce a high level of transparency and trust in the healthcare sector. Based on the immutable data, all health service providers can have access to reliable data that helps to make appropriate decisions. Also, the MoHAP's solution can help to

automate workflow processes and improve sustainability and operational efficiency.

5.3 Permissioned blockchain for medical device tracking in swiss hospitals

Swiss hospitals have witnessed numerous implant and counterfeit scandals in recent years. To overcome such issues, Swiss hospitals have devised a blockchain-based system that enables efficient and trustful tracking of medical devices [73]. Based on a common consensus between the hospitals, all the transactions are stored in blockchain in an immutable and traceable manner. The platform is based on hyperledger technology which is a permissioned blockchain. All the message formats of transactions are aligned with the GS1 standard (Switzerland: GS1 FG BiG Switzerland Ideal Message Healthcare, EDI 3.1 XML). Unlike traditional systems, this infrastructure eliminates the need for a third party while ordering medical devices. Each transaction step in the supply chain is stored in the blockchain platform. The unique identifier of each medical device allows blockchain to make it traceable, which leads to improve patient safety. The blockchain-based platform also enables integration between all actors (e.g., from the manufacturer to smart logistics, and to the patient file) involved in the supply chain, thereby making it possible to design a secure and traceable platform for medical devices in Swiss hospitals.

5.4 Patientory DApp solution

Despite many healthcare institutions are willing to share their data with patients; however, they do not have a secure and easy way to do this. This is challenging because most of the current medical facilities are based on different EHR systems that are unable to communicate with one another. Patientory has developed a decentralized application (DApp) solution that leverages a private permissioned blockchain to enable patients to provide flexible access to their EMR in an interoperable and secure manner [74]. The incredible features of blockchain enable to store patients' medical records across multiple nodes in a decentralized and secure way. Also, it ensures that all the transaction logs are tamper-proof and immutable. Through the Patientory DAPP solution, health data are neither stored on a single location nor controlled by a single entity, thereby providing efficient, easy, and secure sharing of EHR among different medical facilities. Although it is a beta version, the recent survey reveals that the vast majority of users found the DApp a valuable healthcare solution and an excellent tool for managing fitness and diet.

Based on the aforementioned case studies, we conclude that blockchain technology has unprecedented potential to transform and reshape the existing healthcare industries by improving medical record-keeping and access, stopping counterfeit drugs, and enabling traceability for clinical trials, pharmaceuticals, and medical credentials. We believe that most of today's systems leveraged for healthcare data management are centralized that often fall short to provide trusted data provenance, transparency, audit, secure and tamper-proof data storage, reliability, trust, and traceability features. Blockchain technology can help to mitigate such concerns. However, there are several hurdles preventing to witness large scale adoption of blockchain technology into healthcare industries as discussed in the next section.

6 Open research challenges

This section presents key challenges to blockchain mainstream adoption in healthcare data management systems. We outline the underlining causes of these challenges and provide guidelines to new researchers working in the domain. Table 1 summarizes such causes along with their guidelines.

6.1 Scalability

Scalability is one of the key challenges that can limit the mainstream adoption of public blockchains in healthcare industries [75]. Evidently, traditional transaction networks are capable enough to process thousands of transactions per second. For example, Visa can process more than 1700–2000 transactions per second [76, 77]. However, Ethereum blockchains are far behind in terms of transaction speeds as they can only process approximately 20 transactions per second [77]. In case of private blockchains, the lack of scalability is not such an issue, since the processing nodes work under the trusted parties. The scalability issue can be tackled in various ways. One of the possible solutions is the lightning network, which aims to add the second layer to the primary blockchain network to enable faster transactions. Another possible solution is using a sharding technique, which helps to break down transactions into shards and distribute them between the blockchain nodes. In this way, each node does not need to download and save the entire blockchain state, thereby achieving higher transaction speeds through parallelization [76]. Apart from sharding, making a shift toward proof-of-stake consensus can lead to scale up the application. Directed Acyclic Graph (DAG) is another approach, whereby each transaction is linked to multiple transactions [76]. In case of a higher number of transactions, DAG can validate them in a fast manner.

Table 1 Summary of the challenges along with their causes and guidelines

Challenges	Causes	Guidelines
Scalability	(a) Block size and block creation time. (b) Inefficient consensus protocol. (c) Higher confirmation times for a block creation	(a) Sharding technique. (b) Alternatives to proof-of-work. (c) Directed Acyclic Graph approach
Navigate regularity uncertainty	(a) Lack of clarity on compliance. (b) Regulations on blockchain vary from country to country	(a) Ensuring privacy and security of the stored healthcare data
Interoperability	(a) Different consensus models, transaction mechanisms, and smart contract functionalities	(a) Using existing standards in blockchain networks, e.g., IBM and Microsoft are employing GS1 based data standards
Irreversibility and quantum computing	(a) Blockchains are immutable. (b) Conventional digital signatures. (c) High processing capabilities of quantum computing	(a) False or incorrect information should not be stored on blockchain networks. (b) Replacing conventional digital signatures with quantum-resistant cryptography
Tokenization	(a) Lack of regulatory clarity for tokenized assets. (b) Lack of trusted way to ensure consistency between the on-chain crypto tokens and the underlying off-chain assets. (c) Lack of digital identity that is globally and legally-recognized	(a) Introducing tokenization standards and legal infrastructures to enable globally and legally recognized digital identity
Integrating blockchain with existing healthcare systems	(a) Requires considerable changes (e.g., a significant amount of time, meticulous planning, funds, and human expertise) to be made in the existing systems. (b) Extra costs	(a) Healthcare organizations must need to overhaul their current data management systems
Ensuring accuracy of healthcare data	(a) Price discrimination, insurance market competition, human and administrative errors, and avoiding for tax purposes	(a) Healthcare data registers must be cleaned and brought up-to-date before storing data on blockchains
Culture adoption and blockchain developers	(a) Lack of adequately skilled/trained people for managing complex peer-to-peer networks	(a) Initiating employee training programs. (b) Digitally track and assess training completion

6.2 Navigate regulation uncertainty

Another challenge is how to ensure that blockchain technology fits with country's privacy laws (e.g., HIPAA, GDPR) and regulations. Moreover, the lack of clarity on compliance is another challenge restricting organizations to adopt this technology [77]. Blockchain rules and regulations are still in their infancy. These rules and regulations are expected to be mature which means that organizations should need to monitor the changing regulatory framework [78]. Healthcare organizations should directly ask questions from regulators and make suggestions on regulations. Regulations on blockchain vary from country to country. For example, Singapore and Switzerland are using regulatory tokens to speed up the application of blockchain technology; whereas, US regulatory are dependent on individual states instead of the federal government [78]. In the EU, data privacy protection rules are hindering the adoption of public blockchain technology. Although China has banned cryptocurrency, they are supporting regulations to enable the wide adoption of blockchain applications. To make the blockchain a mainstream technology, the healthcare industries need to work with regulators to streamline the blockchain policies and practices.

6.3 Interoperability

To unlock the full potential of blockchain technology in healthcare, it is essential to address the interoperability related challenges. Interoperability plays a vital role to enable interaction between different blockchain networks. Although the absence of standards in blockchain facilitates developers, it poses major challenges in terms of communication due to lack of interoperability. The major problem to interoperability is the existence of multiple blockchain networks that are based on different consensus models, transaction mechanisms, and smart contract functionalities. One of the possible ways to deal with this challenge is to use existing standards in blockchain networks. For instance, IBM and Microsoft are employing GS1 based data standards to enforce interoperability in their blockchain-based supply chain operations. Another solution is to develop new standards. For example, the Enterprise Ethereum Alliance (EEA) introduced a standard version of the Ethereum blockchain.

6.4 Irreversibility and quantum computing

Resilience and irreversibility are two striking features of blockchains [79]. Once data or transactions are stored on the blockchain, they cannot be easily modified. Although blockchain ensures authenticity, it does not ensure accuracy of the stored data [79]. For example, if the stored document contains false or incorrect information, then it will cause resource wastage. Quantum computing is rapidly expanding the computing power of modern systems that pose serious security threats to blockchain systems based on public-key cryptography. Blockchain systems are based on assumptions that classical computers cannot decrypt large numbers quickly [79]. However, quantum computing is an emerging technology that has the potential to solve these difficult problems in the blink of an eye. Hence, it poses a serious threat to blockchain technology in terms of data security. One of the possible solutions to address this challenge is to replace conventional digital signatures with quantum-resistant cryptography.

6.5 Tokenization

In current healthcare systems, most of the organizations, hospitals, and pharmaceuticals do not share their information with patients. Also, it is very hard for patients to verify the accuracy of the data. Tokenization of healthcare data can help to revolutionize the healthcare industry. It is a process that allows to create digital representation for healthcare data and grant-specific usage rights of certain healthcare services. It enables users to access and retrieve their healthcare data without decrypting or re-encrypting. Through tokenization, patients can hold and share their medical record information with anyone, thereby reducing the cost of medical treatment by transferring the power to hold and own data from central intermediaries (e.g., insurance companies, hospitals, pharmaceuticals, to name a few). Upon sharing such data with any research institution, patients can be rewarded with tokens that can be used to offset medical bills. Tokenization is a prerequisite for deploying or adopting blockchain-based solutions in the healthcare industry. However, enabling tokenization has become a very challenging issue due to the lack of regulatory clarity for tokenized assets and trusted way to ensure consistency between the on-chain crypto tokens and the underlying off-chain assets [80].

6.6 Integrating blockchain with existing healthcare systems

Although blockchain technology has potential to bring about major improvements in terms of healthcare data management, there are certain challenges that must be tackled to enable its widespread adoption. Among these challenges, the integration of blockchain with existing systems is of special importance. To make a move to the blockchain system, healthcare organizations must need to overhaul their current systems. However, it is a very crucial challenge because it requires considerable changes (e.g., a significant amount of time, meticulous planning, funds, and human expertise) to be made in the existing systems to facilitate the smooth transition of blockchain technology in the healthcare sector. In certain cases, it is maybe not possible to reconcile blockchain and healthcare systems, and thus in such cases enterprises need to acquire new compatible systems that impose extra costs.

6.7 Ensuring accuracy of healthcare data

Immutability is one of the prime features of blockchain technology. Therefore, it is important to make sure that the healthcare data which need to be transferred onto the blockchain is accurate [81]. The healthcare organizations that are looking to implement blockchain-based solutions are in one of three circumstances, such as they have a paper registry, a digital registry, or a registry that was destroyed [81]. Most of the existing healthcare data registries contain inaccuracies due to various reasons (e.g., price discrimination, insurance market competition, human and administrative errors, avoiding for tax purposes, among others) [81]. Therefore, the healthcare data registers must be cleaned and brought up-to-date before storing data on blockchains. A blockchain registry is very advantageous, especially, in case of tragedies stemming from natural disasters, which led to sensitive health data loss in traditional healthcare systems. Such a solution stores healthcare data on a distributed platform, which is commendably immune from physical destruction.

6.8 Culture adoption and blockchain developers

A cultural shift is required to enable the adoption of blockchain technology in the healthcare sector. Most of current healthcare systems are based on manual and centralized systems, which are vulnerable to data breach and single point of failure, respectively [82]. On the other hand, the current blockchain landscape lacks adequately skilled/trained people for managing complex peer-to-peer networks. Since the last few years, the demand for blockchain-related jobs has been increased by around 2000% [77]. However, finding qualified developers has become a crucial challenge. Blockchain technology is still evolving, so it will take some time for the developer community to adopt it.

7 Conclusions and future recommendations

In this paper, we presented insightful discussions on the integration of blockchain with healthcare systems. We discussed how leveraging blockchain for healthcare industries can lead to manage health data in a decentralized, transparent, accessible, traceable, auditable, trusted, and secure manner. Also, blockchain provides a guarantee of immutability and tamper-proof health data storage. We discussed the features and advantages of blockchain technology to show how it can unlock its full potential for healthcare data management. We discussed the key opportunities offered by blockchain in the healthcare industries. We presented several case studies to show how various healthcare systems have been facilitated and complemented by blockchain technology. We identified and discussed the imperative open research challenges hindering the widespread adoption of blockchain technology in healthcare industries. We conclude that blockchain has the potential to reshape and transform the healthcare industries by bringing significant improvements in terms of operational efficiency, data security, healthcare staff management, and costs. However, integration of the healthcare systems with blockchain engenders some technical challenges, such as blockchain immaturity, scalability, interoperability, stand-alone projects, difficult integration with existing healthcare systems, complexity, and lack of blockchain talent, that need to be addressed. Some of the suggested future recommendations can be found below:

- The convergence of blockchain and artificial intelligence: blockchain and artificial intelligence (AI) are two emerging paradigms individually, but combining the two can lead to fuel efficiency gains in terms of healthcare data analytics. Blockchain can help to overcome some of the fundamental challenges posed by healthcare industries concerning data quality, accessibility, and security. With blockchain, healthcare industries can observe changes in their data in a real-time manner, thereby making it possible to perform quick decisions without human interventions through AI as it can support innovative analytics. Data quality and integration are key factors that can impact the quality of analytics. Blockchain-based healthcare data management helps to resolve both the quality and integration issues that can further enable AI tools to improve the accuracy of analytics results. The convergence of blockchain and AI can lead to revolutionize the healthcare sector.
- Moving toward the IoT-based healthcare systems: the existing healthcare systems need to be integrated with the IoT. The IoT-based medical systems have extensive applicability to numerous healthcare areas. They are capable to transform the routines of medical checks from hospital-centric to home-centric. The IoT-based healthcare systems can offer a plethora of benefits that include real-time monitoring that can save lives in case of emergencies, remote medical assistance through smart mobile applications, end-to-end connectivity and affordability, and tracking and alerts in case of critical circumstances. Storing all the medical data gathered from IoT devices on blockchain systems can enable healthcare organizations and patients to easily manage them in a secure, trusted, transparent, accessible, and traceable manner. In the case of manual healthcare data management systems, there are high chances of inaccuracies due to intentional or unintentional human errors. Therefore, moving such data on blockchain systems can result in resource wastage. Alternatively, storing IoT-based health system data directly on blockchain systems will reduce the chances of inaccuracies, which can help to improve decision-making processes.
- Plugging blockchain technology into legacy healthcare systems: blockchain cannot be easily plugged into existing healthcare databases and enterprise resource planning (ERP) systems. Although certain methods can help in automating the flow of data from ERP systems to DLT, they are complex and expensive. The main challenge associated with the implementation of DLT is how to build out a network of people who are willing to participate and share data amongst themselves by following all the governance rules. One of the possible solutions to build such a network is by offering fair incentive mechanisms as they will motivate more users to participate in DLT platforms.
- Establishing blockchain policies: it is essential to establish stringent policies to enable the widespread adoption of blockchain technology in healthcare industries. Generally, policies are of two types; namely, restrictive and permissive. A good policy should lie between these two extremes. The policy should be designed in a way that it can cover all the goals set by official authorities. It should not contradict with government policies or country rules and regulations. Moreover, the policy should be flexible enough to readjust based on lessons learned and a rapidly changing technological and global landscape. The immense potential of blockchain technology would not be verified without establishing standard policies at the country level.
- Developing secure smart contracts: Smart contracts are reshaping the traditional healthcare industries and their business processes by enabling contractual terms of agreements in an automated manner. They do not involve any intervention of third parties, thereby cutting

down administrative costs, improving the efficiency of healthcare processes, and reducing risks. Even though smart contracts are bringing a new wave of innovations in healthcare processes; however, there are certain challenges related to smart contract creation (readability and functional issues), deployment (contract correctness and dynamic control flow), execution (trustworthy oracle, transaction-ordering dependence, and execution efficiency), and completion (privacy, security, and scam) [28]. Such challenges need to be resolved in the future to witness the full potential of blockchain technology.

- Latency and throughput bottlenecks: In public blockchains, there are large number of nodes that need to reach a consensus to verify a transaction. To process transactions so that consensus can be reached, each node needs to have access to the entire blockchain network. This causes latency issues in public blockchains. On the other hand, providing access to the entire blockchain can pose certain privacy and security threats. Another crucial issue is how to enhance the throughput of public blockchains. Adequate attention must be given to alleviate such problems so that blockchain can become a mainstream technology.

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Compliance with ethical standards

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